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EXTRAPOLATION OF THE ISABELLE DESIGN TO 400 x 400 GeV[*]

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Summary

Consideration of a national program for the development of new high energy facilities during the next ten years suggests that the most appropriate energy for proton storage rings may be higher than the 200 x 200 GeV of the present ISABELLE design. It has been indicated that 300 x 300 GeV or 400 x 400 GeV may provide a more reasonable step to maximize the scientific potential of the next major proton storage ring facility. A preliminary analysis of the design consequences of changing the ISABELLE energy to 300 x 300 GeV and 400 x 400 GeV is given, keeping the luminosity, maximum field and most of the original design parameters unchanged. It is concluded that the ISABELLE concept can be extrapolated to 400 x 400 GeV without any unmanageable technical problems and that even higher energies seem to be feasible.

I. Introduction

Consideration of a national program for the development of new high energy facilities during the next ten years suggests that the most appropriate energy for proton storage rings may be higher than the 200 x 200 GeV of the present ISA design.[1,2] The present center-of-mass energy of FNAL is approximately 25 GeV. That for the ISR is about 50 GeV, which in retrospect is not sufficiently higher than that at FNAL to make accessible a new range of physical phenomena. A next realistic step in a conventional high energy accelerator should be in the range of 100 GeV (e.g. 5 TeV protons-on-protons at rest). Taking this into consideration, a maximum ISA energy of 300 x 300 GeV or 400 x 400 GeV may provide a more reasonable next step to maximize the scientific potential of the next major storage ring facility.

The purpose of this paper is to provide a preliminary analysis of the design consequences of changing the maximum energy to 300 x 300 GeV and 400 x 400 GeV, following Ref. 2 in detail.[†] In Section II, we shall consider a design appropriate to a maximum energy of 400 GeV, keeping the luminosity, maximum magnetic field, and most of the other original design parameters unchanged. In Section III, we shall explore the consequences of changing other design parameters.

It is clear that scaling the bending radius with maximum energy will lead to a major increase in construction cost. The purpose of this paper is to examine the technical problems associated with going to higher energy in this way. Optimization of parameters to minimize cost can be considered subsequently.

II. Design for 400 x 400 GeV Maximum Energy

In this section, we shall explore the consequences of an increase in maximum energy to 400 GeV keeping the following parameters unchanged:

1. Maximum bending field = 40 kG.
2. Basic lattice design.
3. Number, length and type of straight section insertions.
4. Luminosity at maximum energy = 10^{33} cm^{-2}s^{-1}
5. Beam pipe diameter = 8 cm.
6. Maximum permissible beam-beam tune shift = 0.005.
7. Radiofrequency stacking voltage = 12 kV/turn.
8. ISA harmonic number for acceleration = 2.
9. Radiofrequency voltage = 40 kV/turn.

Some of these items require further discussion.

A. Basic Lattice, Including Straight Sections

In first approximation, the lattice structure will be that in the present design, and the primary change will be the doubling of the bending radius and number of regular cells for 400 x 400 GeV.[‡] Although a few experiments (particularly those involving very small angles and those which need long path lengths for particle identification) imply the need for an increase in the length of the straight sections, most experiments (including those which are likely to be most exciting at higher energy) will have ample space at 400 x 400 GeV with the present geometry. Furthermore, an increase in the free-space length around the interaction region will make high luminosity harder to achieve. For these reasons we assume here a doubling of the bending radius (and length) of the curved sections and no increase in length of the straight sections.

The present 200-GeV design involves the following approximate contributions to ν_h, ν_v and γ_t (the transition energy in units of Mc^2).

200-GeV ISA

	Curved Sections	Straight Sections	Total
ν_h	12.0	11.1	23.1
ν_v	12.0	8.6	20.6
γ_t	12.0	7.0	19.0

With no change in the phase advance per cell at 400 GeV, γ_t would be 2 x 12.0 + 7.0 = 31.0 which would be too close to the injection energy of 28.5 GeV corresponding to γ_{inj} = 31.4. In the next subsection, we shall show that a value of γ_t = 25.0 will lead to no troublesome injection problems in the ISA. This can be easily achieved by decreasing the average β^{-1} ($< \beta^{-1} > = \nu/R$) by a factor 3/4 in the curved section lattice, and leads to no increase in the required aperture. Furthermore, no difficulties are expected in matching the regular lattice to the straight section focusing system. With the average β^{-1} in curved sections taken to be 3/4 of the present design value, the orbit parameters (easily adjusted to a location in the "diamond" which avoids the relevant resonances are:

400 GeV

	Curved Sections	Straight Sections	Total
ν_h	18.0	11.1	29.1
ν_v	18.0	8.6	26.6
γ_t	18.0	7.0	25.0

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[*] Work performed under the auspices of the U.S. Energy Research & Development Administration.

[†] Meanwhile, considerable modifications of the design of Ref. 2 have been suggested especially with respect to the lattice. However, it is felt that these will not change the general conclusions of this paper.

[‡] The length of the momentum matching sections will also have to be doubled.

The sextupole fields in the elements of the regular cells, required to produce the proper working line, will be somewhat smaller than in the 200-GeV design. This is the result of having twice as many elements available together with an increase in the average β and only a small decrease in the average X_p function in the cells.

B. Injection Effects Due to High Transition Energy

At injection, with $\gamma_{tr} = 25$ and $\gamma_{inj} = 31.4$, the coefficient η, expressing the dependence of angular velocity on momentum and given by $1/\gamma_{tr}^2 - 1/\gamma^2$ has the value 0.58×10^{-3} compared to 1.5×10^{-3} in the 200-GeV ISA design. With an unchanged RF voltage of 12 kV in the ISA stacking system, the AGS voltage required for matching of the AGS bunches into ISABELLE will be 53 kV instead of 36 kV in the 200 GeV design (obtained from the relationship $h_{AGS}V_{AGS}/R_{AGS}^2\eta_{AGS} = h_{ISA}V_{ISA}/R_{ISA}^2\eta_{ISA}$). This leads to tighter bunches and an increase in the longitudinal space-charge detuning in the ISA injection orbit. However, the space-charge parameter η_{sc}, which is the ratio between the longitudinal space-charge force constant and the RF force constant has been calculated to be ~ 0.25, still a perfectly acceptable value.

C. Luminosity and Beam-Beam Tune Shift

Approximate expressions for L and $\Delta\nu_V$ can be used to determine the effect of increasing the maximum energy to 400 GeV. In particular, if one neglects variation in beam size in the interaction region, as well as long-range interaction effects between the beams, one obtains

$$L = \frac{(I/e)^2}{b\alpha c\sqrt{2}}$$

$$\Delta\nu_V = \frac{(I/e)\ r_p\beta_V^*\sqrt{2}}{\gamma b\alpha c}$$

$$L = \frac{(I/e)\ \gamma\ \Delta\nu_V}{2r_p\beta_V^*}\quad .$$

Here b/2 is the rms beam radius, β_V^* is the value of β_V at the center of the interaction region, and α is the crossing angle which is selected to give the maximum permissible value of $\Delta\nu_V$ in order to maximize L.

If β_V^* and $\Delta\nu_V$ (at maximum energy) are unchanged from the present design, a luminosity of 10^{33} cm^{-2}s^{-1} can be obtained at 400 x 400 GeV with I = 5 A (half the present design of 10 A). This simplifies a number of problems connected with injection and acceleration in the storage rings (stacking, effect of pressure bumps, image effects, stored energy in the beam), but leads to half the present design luminosity when the ring is operated at 200 x 200 GeV. (One might have to go to a slightly larger value of β_V^* because of an increase in the distance between the interaction region and the nearest focusing element brought about by the requirement of longer bending magnets. However, this should not amount to more than a 20% increase and could be compensated for by going to beam currents slightly above 5 A to maintain the luminosity of 10^{33} cm^{-2}s^{-1}.)

D. Aperture Requirements

1. Betatron Emittance. In order to reduce the average of β^{-1} to 75% of the present design value in the curved sections, the betatron phase shift per cell will be reduced from 90° to 67.5°. This leads primarily to an increase in β_{min}, leaving β_{max} essentially unchanged, and requires no change in the aperture.

2. Momentum Spread of the Stacked Beam. Assuming no change in the stacking efficiency in longitudinal phase space, one could reduce the momentum spread of the stacked beam. This however, may lead to problems with longitudinal instabilities, and so we have assumed that the stacking is arranged to yield the same momentum spread as in the present design. (This should also make the stacking process easier.) The momentum compaction, X_p, will be reduced by about 20% in going to half the bending angle per cell and a betatron phase shift of 67.5°. As a result the aperture requirement due to momentum spread will be reduced by 0.25 cm.

3. Shutter on Injection Kicker. No change.

4. Sagitta. Doubling of the bending radius magnitudes lowers the sagitta requirements by a factor 2, reducing the aperture requirement by an additional 0.65 cm.

5. Clear Space. No change.

As a result of the increase in maximum energy to 400 x 400 GeV, the aperture requirements are reduced by almost 1 cm. Although a reduction in beam pipe diameter and magnet aperture should be possible (the reduced current reduces the aperture requirements related to the pressure bumps), we shall here retain the inside diameter of 8 cm for the vacuum chamber in the present design.

E. Intensity Related Effects

1. Space-Charge Detuning. Image charges and currents due to an imperfectly centered beam will produce a tune shift proportional to the current and the square of the circumference. Our 400 x 400-GeV design increases this tune shift by a factor 1.3, placing a modest, but acceptable, additional burden on "prestressing" the working line.

2. Resistive Wall Instability. In the 200-GeV ISA design the tune spread required to stabilize the resistive wall instability is predicated on the real part of the frequency shift. The same situation holds for the 400-GeV design. The real part of frequency shift is proportional to the current and the square of the circumference, and inversely proportional to the tune and to the beam transverse area. Our 400 x 400-GeV design leads to a reduction in the frequency shift to 75% of its value in the present 200 x 200-GeV design. This will ease the problems associated with compensating for this tune shift.

3. Longitudinal Instabilities.

a. Coasting Beam. Injecting closer to transition affects the stability criterion with regard to self-bunching of the stacked coasting beam at the injection energy. The condition required to avoid such instabilities is given by*

$$IZ_n < n\eta\ E/e(\Delta p/p) \times \Delta p_t/p$$

where I is the current, Z_n is the coupling impedance for the n'th harmonic of the revolution frequency, $\Delta p/p$ is the full width at half-height of the momentum distribution and $\frac{1}{2}\ \Delta p_t/p$ is the width at half-height of its low energy tail. For $\eta = 0.58 \times 10^{-3}$, I = 5 A, $\Delta p/p = 2.0073$ and $\Delta p_t/p = 0.0007$ one obtains $Z_n/n < 16\ \Omega$ compared to 21 Ω in the 200-GeV design.

The RF stacking system in the 400-GeV design described here would operate at h = 65. If one maintains the 200-GeV design impedance of 400 Ω, reducible to 40 Ω by feedback, the requirement $Z_n/n < 16\ \Omega$ is easily met. Again, as in the 200 GeV design, some stirring up of

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*A different formula was erroneously given in Ref. 2 leading to much larger values of Z_n/n.

longitudinal phase space is to be expected at the initial stages of the stacking process when $(\Delta p/p \times \Delta p_t/p)/I$ is small. A pessimistic estimate for the time constant of the instability, can be made by assuming that there is no Landau damping. Under these conditions the growth time is given by $\tau = 1/\omega_o \times (2\pi E/eIZ_n\eta n)^{\frac{1}{2}}$, where ω_o is the angular revolution frequency. For a 1 A stacked beam one obtains $\tau \approx 3$ sec compared to $\tau \approx 1$ sec in the 200-GeV design. Hence, although the threshold for the instability corresponds to a lower impedance in the 400-GeV design, the undamped growth rate is lower.

For the accelerating system consisting of 4 cavities and having a total impedance of 700 Ω, the stability criterion is met neither in the 200 GeV nor in the 400-GeV design. The accelerating cavities will have to be shorted and the short circuit of the cavities removed one by one in the beginning of the rebunching process so that the coasting beam will see only ¼ of 700 Ω. Even so some instability will develop. However, with a current of 5 A in the 400-GeV design, one gets an increased undamped growth time of 1.2 s compared to 0.3 s in the 200-GeV ISA.

Even slower growth rates will result during the time it takes to again short the cavities after the end of acceleration.

b. Bunched Beam. Possible longidudinal instabilities of bunched beams are only to be expected during the stacking process. With only two bunches circulating during acceleration, all oscillation modes are stable. (A small contribution from the resistive wall effect can be neglected.)

The stability criterion for the m'th mode (m = 1 for dipole, m = 2 for quadrupole, etc.) of oscillation is given by

$$\left|\frac{\sqrt{m}\,\Delta\omega_{sc}}{\omega_s}\right| + \left|\frac{\Delta\omega_m}{\omega_s}\right| \leq \frac{1}{4}\frac{S}{\omega_s} \quad .$$

Here $\Delta\omega_{sc}$ is the shift in the synchrotron angular frequency ω_s due to space charge, $\Delta\omega_m$ is the shift in ω_s due to a resonator and S is the spread in ω_s between the center and the edge of the bunch. $\Delta\omega_{sc}/\omega_s = \frac{1}{2}\eta_{sc}$ where η_{sc} is the space-charge parameter mentioned in part B of this Section. $\Delta\omega_m/\omega_s = 0.16\{[Z(\omega)I/V \cos\varphi_s][M/Bh]\, D\, F_m(\omega)\}$, where ω is the frequency of the oscillation mode [V is the peak voltage per turn, φ_s the synchronous phase, M number of bunches, and B is the bunching factor. D is a form factor depending on the number of bunches and the Q of the cavities and $F(\omega)$ is then a form factor depending on the frequency ω, having a maximum for $\omega = m\pi\ell/c$ where ℓ is the bunch length]. S/ω_s is a function of B and φ_s. It is biggest for $\sin\varphi_s = 0$ and $B = 1.0$. In the 200-GeV design $\Delta\omega_{sc}/\omega_s > \frac{1}{4} S/\omega_s$ and the bunches are inherently unstable. However, assuming a reasonable value for $Z(\omega)$ the subsequent growth rates of the instabilities are sufficiently slow to allow for a feedback system to inhibit them. As in the case of the coasting stacked beam, the system of the injected bunches is again inherently more unstable in the 400-GeV ISA (due to an increase in $\Delta\omega_{sc}/\omega_s$ and a decrease in S/ω_s). However, the growth rates connected with the undamped instabilities will be smaller (growth times larger) due to a decrease in current and the synchrotron angular frequency through the dependence on η and R, facilitating the problems of controlling the instabilities.

F. Injection Field

For a maximum energy of 400 GeV, the magnetic fields at injection will be half their value in the 200-GeV design. This corresponds to an increase of a factor 13.6 instead of 6.8 during acceleration. For comparison, the corresponding factor in the FNAL ring is 50 at 400 GeV.

With the maximum magnetic field unchanged, the most important change will be at injection due to the diamagnetic behavior of the superconductor. However, we expect that these effects can be compensated for by the tuning and correcting windings which are already present to correct high field saturation effects. The additional requirements on these windings should not be too severe, since the new injection field of 3 kG is not particularly low.

G. Acceleration

1. Acceleration Time. With the same voltage per turn and a synchronous phase as in the 200-GeV design the time required to accelerate from 30 to 400 GeV will be increased from 2 to 7 min.

2. Momentum Spread at 30 GeV. The matched momentum spread of a bunched beam varies as $\eta^{-\frac{1}{4}}$. At 30 GeV it will be larger in the 400-GeV design by a factor of 1.27. This will not pose a problem because of the relaxed aperture requirements mentioned in part A of this Section.

3. Crossing of Nonlinear Resonances. The effect of repeated crossings of nonlinear resonances during acceleration were investigated for the 200-GeV ISA design. It was concluded that as long as the working line stayed away from the 3rd and 4th order resonances the transverse emittance growth was negligible during the acceleration time. This conclusion is still valid for an acceleration time of 7 min. (Emittance doubling times for crossing 5th order resonances were estimated to be $\sim 10^4$ s.) The synchrotron frequency, determining the speed at which the resonances are traversed, varies as $\eta^{\frac{1}{2}}$ and at 30 GeV is decreased by a factor of 1.6 in the present 400-GeV design. This is an insignificant change and will not alter the assumptions of the fast crossing made for the estimates of emittance doubling times.

4. RF System. Keeping 40 keV/turn and h = 2, the only change required in the accelerating RF system is the frequency. It will be lowered from 0.22 MHz to 0.14 MHz.

III. Possible Modification of Parameters

We have examined the basic design considerations (apart from cost) associated with a step to 400 x 400 GeV. Although our conclusion is that there are no major problems in the higher energy design, it may be worthwhile to consider briefly the effect of changes in some of the parameters which have been discussed in Section II.

A. Maximum Energy

If cost or other considerations limit the maximum energy to 300 x 300 GeV, the design considerations will obviously be intermediate between those in Section II and the present design. Since the increase in ν will not be as large as in the 400 x 400 GeV case, the transition energy will only increase to 25 Mc^2 with the phase advance per cell of the 200 x 200-GeV design, and there will be no need to modify the lattice design to increase β.

Increase in the maximum energy beyond 400 x 400 GeV should also be possible, but this will require a significant increase in β in order to keep the transition energy sufficiently far below injection. Among those items which will have to be examined more carefully are: collective effects (tune shifts and instabilities), the low field compensation of magnetization in the superconductor, and the design and optimum length of the straight section insertions.

B. Current

One of the consequences of the design in Section II is the reduction of the luminosity at 200 x 200 GeV. In order to retain the present design value of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 200 x 200 GeV, the current will have to be increased to its present design value of 10 A. This, however, will lead to severe problems with regard to injection and stacking (twice the number of particles as in the present design), collective effects, stored beam energy, etc., and is, therefore, to be considered as undesirable.

C. Magnetic Field

Questions have been raised about using a niobium-tin superconductor to reach higher fields at higher temperatures. If this proves to be technologically sound, it will, of course, modify the present ISA design significantly as well as the design in Section II. Our philosophy has been to view an increase in the maximum magnetic field as an "improvement" which will permit reaching higher energies. Alternatively, one could envision maintaining the present ISA design, but go up in energy with higher magnetic fields.

D. Aperture

As discussed in Section II D, constraints on the aperture appear to be reduced in the 400 x 400-GeV design. A reduction in vacuum pipe diameter from 8 cm to 7 cm may be possible, especially for a maximum current of 5 A. This should provide some reduction in the magnet and dewar costs.

E. Length of Straight Sections

If longer straight section insertions or longer unobstructed regions should prove to be very important in some of the 400 x 400-GeV experiments, appropriately designed insertions will have to be included. Apart from cost, there appear to be no major obstacles to the design of such longer insertions.

IV. Conclusions

We have examined the technical problems associated with increasing the maximum ISA energy to 400 x 400 GeV keeping the maximum magnetic field, the maximum luminosity, and the length of the straight section insertions the same as in the present ISA design at 200 x 200 GeV. Our conclusion is that there are no unmanageable technical problems with such a design; in fact, this conclusion probably holds for even higher energy.

In the course of our analysis, the following specific considerations were addressed:

1. Problems with the increased transition energy were brought under control by a modest increas in β_{min} in the curved sections (β_{max} remains essentially unchanged).
2. Problems with the aperture are less severe because of the reduction in the sagitta requirement at 400 GeV.
3. The current necessary to reach a maximum luminosity of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 400 x 400 GeV is $I = 5$ A. This reduction in current from the present design keeps the longitudinal and transverse instabilities from becoming more serious. It also avoids problems due to excessive beam stored energy.
4. The accelerating voltage can be kept the same, but its frequency will be reduced. The overall acceleration time is increased by about a factor of 3.5.

References

1. V.F. Weisskopf, Chairman, "Report of the Subpanel on New Facilities of the High Energy Physics Advisory Panel to the Atomic Energy Commission", (June 1974).

2. H. Hahn and M. Plotkin, Ed., "A Proposal for Construction of a Proton-Proton Storage Accelerator Facility ISABELLE", BNL Report 18891 (May 1974). All of the formulas used in this report can be found here.